Evolution as context-driven actualisation of potential: toward an interdisciplinary theory of change of state

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It is increasingly evident that there is more to biological evolution than natural selection; moreover, the concept of evolution is not limited to biology. We propose an integrative framework for characterising how entities evolve, in which evolution is viewed as a process of context-driven actualisation of potential (CAP). Processes of change differ according to the degree of non-determinism, and the degree to which they are sensitive to, internalise and depend upon a particular context. The approach enables us to embed phenomena across disciplines into a broad conceptual framework. We give examples of insights into physics, biology, culture and cognition that derive from this unifying framework.

The term evolution is often construed as shorthand for Darwinian evolution – a process of descent with modification, whereby a species adapts to an environment through iterations of replication with random variation followed by natural selection. Darwin's theory united previously disparate phenomena, and paved the way for further inquiry. However, it contributes little to our understanding of developmental and ecological processes. Also, applications of Darwinism in the social sciences have not caught on, suggesting there is more going on in the evolution of cultures and economies than natural selection. Moreover, the concept of evolution extends beyond the biological and social sciences; physicists use the term to refer to dynamical change of state in the absence of a measurement, without implying that natural selection is involved. Thus natural selection is only part of the picture of how entities evolve.

This paper outlines how the concept of evolution has been used in different fields, summarises the limitations of neo-Darwinism as a general theory of evolution, and sketches what a general theory of evolution might look like. The basic idea is that all entities evolve through a reiterated process of *interaction* with a context; thus the process is referred to as 'context-driven actualisation of potential', or 'CAP'. By 'potential' we do not mean something determined or preordained; in fact, the actual is but a realised fraction of the spectrum of what is potential. Indeed, different forms of evolution differ according to the degree of non-determinism, as well as the degree of contextuality and retention of context-driven change. The CAP framework has been applied in a detailed or technical manner to specific domains such as physics[1] and creativity.[2] The goal of the present paper

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is to propose a scheme for uniting physical, biological and cultural evolution, not reductively, but through a process that has been referred to as interlevel theorising.[3] The value in such a unifying vision is not universally agreed upon. While many believe it to play a vital role in scientific explanation,[4] others warn it may lead to oversimplification and distortion.[5] Without actively engaging in this debate, we note that the framework proposed here was not sought after but rather landed on our doorstep. We acknowledge the existence of genuine and formidable barriers to interdisciplinarity,[6] but hope this fledgling effort will add to the accumulating evidence that there is much to be gained by sharing perspectives and methods across fields that superficially appear to be vastly different.[7] Indeed the framework described here has already borne fruit: it suggests a unifying scheme for the two kinds of change in quantum mechanics, offers a fresh perspective on issues such as selection and fitness in biology, and clarifies how the concept of evolution applies to culture and creative thought.

LIMITATIONS OF THE NEO-DARWINIAN FRAMEWORK

This section outlines the shortcomings of natural selection as a theory of how biological organisms evolve, and shows that it runs into even more serious problems when applied to the evolution of culture, creative thought and physical objects and particles.

Evolution of biological form

Darwin's theory of natural selection threw light on the perplexing question why some traits thrive at the expense of others. In what has come to be called the neo-Darwinian paradigm, the basic idea of random variation and natural selection has been vastly extended by knowledge of the underlying genetic mechanisms, and by mathematical formalisation by population biologists. However, it is becoming increasingly evident that neo-Darwinism, powerful though it is, cannot account for all, or perhaps even most, biological change.[8] The concept of natural selection offers little in the way of explanation for how biological forms and phenotypes arise in the first place. (Natural selection may be a powerful tool for describing biological change, but it can tell you little about the fitness of the offspring you would have with one healthy mate as opposed to another.) Moreover, non-Darwinian processes – such as autopoiesis,[9] emergence,[10] symbiosis,[11] punctuated equilibrium[12] and epigenetic mechanisms[13] – play a vital role. What is more, the generation of variation is not completely random; convergent pressures are already at work prior to the physical realisation of organisms. First, mating is often assortative – mates are chosen on the basis of traits they possess or lack, rather than at random, not just in humans,[14] but in other species as well,[15] including plants[16] – and relatives are avoided as mates. Second, following Cairns' initial report,[17] there has been increasing evidence of *directed* mutation, where the frequency of beneficial mutations is much higher than chance, particularly in environments to which an organism is not well adapted. Furthermore, the concept of fitness, a cornerstone of the neo-Darwinian enterprise, is problematic.[18] In sum, there is more going on in evolution than random variation and natural selection.

Cultural evolution

Culture too is often said to be a process of evolution, at least in the general sense of change in response to environmental constraints such that new solutions grow out of and build upon old ones.[19] Inspired by Dawkins' notion of 'universal Darwinism' – the idea that natural selection is not restricted to the physical structure of organic life, but could work with other underlying materials[20] – Darwinism has been adapted to develop mathematical[21] and computational[22] models of cultural evolution. It has also been applied less formally to units of culture (sometimes referred to as memes),[23] and to the analysis of economic growth,[24] financial markets,[25] social customs[26] and artefact design.[27] These studies occasionally fall under attack,[28] but are more often simply ignored. Common critiques are that ideas are not generated randomly but strategically, cultural artefacts are not self-replicators, and cultural evolution is Lamarckian while biological evolution is not. The suggestion that units of culture (like songs or architectural plans) are replicators has been particularly problematic. An idea is not a replicator because it does not consist of self-assembly instructions; it may *retain* structure as it passes from one individual to another, but it does not *replicate* it.[29]

Thus, not only does natural selection fail to provide an integrative framework for biology, but it has not had significant impact when applied to the social sciences.

Creative thought

Cognition too has been put in Darwinian terms. While some philosophers describe the growth of knowledge as Darwinian in the sense that conjectures must be refutable, i.e. able to be selected against,[30] others[31] go further, arguing that a stream of creative thought is a Darwinian process. The basic idea is that we generate new ideas through variation and selection – 'mutate' the current thought in a multitude of different ways, select the variant that looks best, mutate *it* in various ways and select the best variant, and so forth until a satisfactory idea results. Thus thought is viewed as a series of tiny selections. This view, however, has not caught on. As Pinker puts it, 'a complex meme does not arise from the retention of copying errors . . . The value added with each iteration comes from focusing brainpower on improving the product, not from retelling or recopying it hundreds of thousands of times in the hope that some of the malaprops or typos will be useful.'[32] Indeed attempts to develop the Darwinian view of cognition formally must fail, because natural selection theory, as mathematically formulated by population geneticists, requires multiple, distinct, simultaneously actualised replicators that differ in their rate of replication. Not only is a thought or idea not a replicator, as noted above, but each thought changes the context against which the next is evaluated; they are not simultaneously selected amongst.[33] Creative ideas are contextually elicited, not generated randomly, and their refinement is a matter of honing in by reevaluating successive iterations from different perspectives until a goal is met.[34] Is there nevertheless some sense in which thought can be said to evolve?

Evolution of objects and particles

The term 'evolution' is used quite differently in physics. States of a particle are represented by unit vectors of a mathematical space referred to as a 'complex Hilbert space'.[35] A measurement on a particle[36] always has a set of special states associated with it, the 'eigenstates'[37] (end states). An eigenstate is a state that does not change under the influence of the measurement. However, if the particle is in a 'superposition state'[38] then the change of state provoked by the measurement is such that this superposition state changes to one of the eigenstates of the measurement. This change of state from a superposition state to an eigenstate is referred to in the quantum jargon as 'collapse'.[39] Evolution is what happens in the absence of collapse. Thus, evolving is what the quantum entity is doing when no measurement is taking place. This evolution is described by the Schrödinger equation, and it is considered a fundamentally different kind of change from collapse under the influence of a measurement.

Clearly physicists are using the term 'evolution' to refer to something quite different from what it means in the biological or social sciences. Yet in all cases it refers to a process of change, and there is a concern for the history of change, both internal and external to the entity, and how that history affects and reveals itself in the entity's present structure.

EVOLUTION AS CONTEXT-DRIVEN ACTUALISATION OF POTENTIAL

We have seen that the neo-Darwinian paradigm does not provide a complete account of evolution, not in biology, nor elsewhere where the term is used. We now look at a more general scheme for change of the state of an entity under the influence of a context.

Deterministic versus non-deterministic change of state

Since we do not always have perfect knowledge of the state of the entity, the context, and the interaction between them, a general description of an evolutionary process must be able to cope with non-determinism. Evolutionary systems differ with respect to the degree of determinism involved in the changes of state that the entity undergoes. Consider an entity – whether it be physical, biological, mental or of some other sort – in a state $p(t_i)$ at an instant of time t_i. If it is under the influence of a context $e(t_i)$, and we know with certainty that $p(t_i)$ changes to state $p(t_{i+1})$ at time t_{i+1}, we refer to the change of state as 'deterministic'. Newtonian physics provides the classic example of deterministic change of state. Knowing the speed and position of a ball, one can predict its speed and position at some time in the future. In many situations, however, an entity in a state $p(t_i)$ at time t_i under the influence of a context $e(t_i)$ may change to any state in the set $\{p_1(t_{i+1}), p_2(t_{i+1}), \ldots, p_n(t_{i+1}), \ldots\}$. When more than one change of state is possible, the process is 'non-deterministic'.

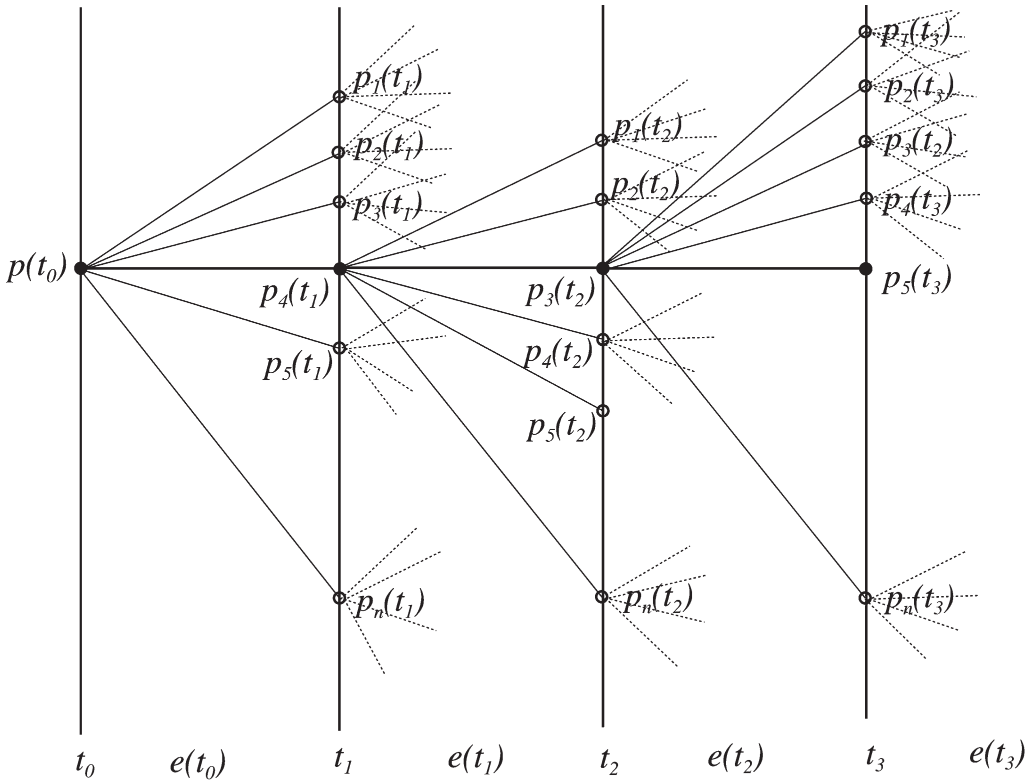
Non-determinism with respect to state of entity

Non-deterministic change can be divided into two kinds. In the first, the non-determinism originates from a lack of knowledge concerning the state of the entity $p(t_i)$ itself. This means that deep down the change is deterministic, but since we lack knowledge about what happens at this deeper level, and since we want to make a model of what we know, the model we make is non-deterministic. This kind of non-determinism is modelled by a stochastic theory that makes use of a probability structure that satisfies Kolmogorov's axioms.[40]

Non-determinism with respect to context

Another possibility is that the non-determinism arises through lack of knowledge concerning the context $e(t_i)$, or how that context interacts with the entity.[41] It has been proven that the stochastic model describing this situation necessitates a non-Kolmogorovian probability model (where Bayes's axioms of conditional probability do not hold). A

Kolmogorovian probability model (such as is used in population genetics) cannot be used.[42] It is only possible to ignore the problem of incomplete knowledge of context if all contexts are equally likely, or if context has a temporary or limited effect. Because the entity has the potential to change to many different states (given the various possible states the context could be in, since we lack precise knowledge of it), we say that it is in a 'potentiality state' with respect to context. This is schematically depicted in the adjacent figure.



Graphical representation of a general evolution process. Contexts $e(t_0)$, $e(t_1)$, $e(t_2)$, $e(t_3)$ at times t_0, t_1, t_2, t_3 are represented by vertical lines. States of the entity are represented by circles on vertical lines. At time t_0 the entity is in state $p(t_0)$. Under the influence of context $e(t_0)$, its state can change to one of the states in the set $\{p_1(t_1), p_2(t_1), p_3(t_1), p_4(t_1), \ldots, p_n(t_1), \ldots\}$. These potential changes are represented by thin lines. Only one change actually takes place, the one represented by a thick line, i.e. $p(t_0)$ changes to $p_4(t_1)$. At time t_1 the entity in state $p_4(t_1)$ is under the influence of another context $e(t_1)$, and can change to one of $\{p_1(t_2), p_2(t_2), p_3(t_2), p_4(t_2), \ldots, p_n(t_2), \ldots\}$. Again only one change occurs, i.e. $p_4(t_1)$ changes to $p_3(t_2)$. The process then starts all over again. Under the influence of a new context $e(t_2)$, the entity can change to one of $\{p_1(t_3), p_2(t_3), p_3(t_3), p_4(t_3), \ldots, p_n(t_3), \ldots\}$. Again only one change happens: $p_3(t_2)$ changes to $p_5(t_3)$. The dashed lines from states that have not been actualised at a certain instant indicate that much more potentiality is present at time t_0 than is explicitly shown. For example, if $p(t_0)$ had changed to $p_2(t_1)$ instead of $p_4(t_1)$, which was possible at time t_0, then context $e(t_1)$ would have exerted a different effect on the entity at time t_1 such that a new vertical line at time t_1 would have to be drawn, representing another pattern of change

We stress that a potentiality state is just waiting for its time to come along, not predetermined, at least not insofar as our models can discern, possibly because we cannot precisely specify the context that will come along and actualise it. Note also that a state is only a potentiality state *in relation to* a certain (incompletely specified) context. It is possible for a state to be a potentiality state with respect to one context, and a deterministic state with respect to another. More precisely, a state that is deterministic with respect to a context can be considered a limit case of a potentiality state, with zero potentiality.

In reality the universe is so complex that we can never describe with complete certainty and accuracy the context to which an entity is exposed, and how it interacts with the entity. There is always some possibility of even very unlikely outcomes. However, there are situations in which we can predict the values of relevant variables with sufficient accuracy that we may consider the entity to be in a particular state, and other situations in which there is enough uncertainty to necessitate the concept of potentiality. Thus a formalism for describing the evolution of these entities must take into account the degree of knowledge we as observers have about the context.

A mathematics that describes both contextual and uncontextual change

We have seen that a description of the evolutionary trajectory of an entity may involve non-determinism with respect to the state of the entity, the context, or how they interact. An important step toward the development of a complete theory of evolution is to find a mathematical structure that can incorporate all these possibilities.[43] There exists an elaborate mathematical framework for describing the change and actualisation of potentiality through contextual interaction that was developed for quantum mechanics. However it has several limitations, including the linearity of the Hilbert space, and the fact that it can only describe the extreme case where change of state is maximally contextual. Other mathematical theories, such as state–context–property (SCOP) systems,[44] lift the quantum formalism out of its specific structural limitations, making it possible to describe non-deterministic effects of context in other domains.[45] The original motivation for these generalised formalisms was theoretical (as opposed to the need to describe the reality revealed by experiments). With these formalisms it is possible to describe situations with *any* degree of contextuality. In fact, classical and quantum come out as special cases – quantum at one extreme, of complete contextuality, and classical at the other, complete lack of contextuality.[46]

This is why SCOP formalisms lend themselves to the description of context-driven evolution. For example, let us say an entity undergoes a change of state from $p_0(t_0)$ to $p_4(t_1)$. The change of state of the entity may evoke a change in its context (or in the sort of context it is subsequently susceptible to), or the context may change of its own accord. Under the influence of this (possibly new) context, which we call $e(t_1)$, there may be many potential states it could change to. We denote this set of states $\{p_1(t_2), p_2(t_2), \ldots, p_n(t_2), \ldots\}$. At time t_2, one of these states, for example $p_3(t_2)$, may actualise. And so forth, recursively. The states $p(t_0), p(t_1), p(t_2), \ldots, p(t_i), \ldots$ constitute the trajectory of the entity through state space, and describe its evolution in time. Thus, the general evolution process is broadly construed as the incremental change that results from recursive, context-driven actualisation of potential, or CAP. A model of an evolutionary process may consist of both deterministic segments, where the entity changes state in a way that follows predictably given its previous state and/or the context to which it is exposed, and/or non-deterministic segments, where this is not the case.

Degree of sensitivity to context

Besides degree of non-determinism and whether it stems from lack of knowledge concerning entity or context, another parameter that differentiates evolving entities is the degree of sensitivity to context, or more precisely the degree to which a change of state of context evokes a change of state of the entity. This can vary from not just one entity to another but also one environment to another. In an environment that rarely affords contexts that induce a change of state (or the induced changes of state are small), a given entity may be completely adapted. However, in an environment that affords contexts that induce frequent or large scale change, the same entity may barely survive.

Degree to which context-driven change is retained

Sensitivity to context is just one facet of contextuality. An entity may be sensitive – readily undergo change of state due to context – but through regulatory mechanisms or self-replication have a tendency to return to its previous state. An example of a situation where context-driven change is retained is a rock breaking in two. An example of where it is not is the healing of an injury.

Context independence

The extent to which a change of context threatens the survival of the entity can be referred to as context dependence. The degree to which an entity is able to withstand not just its particular environment, but *any* environment, can be referred to as 'context independence'. Sensitivity to and retention of context can lead, in the long run, to *either* context dependence or context independence. This can depend on the variability of the contexts to which an entity is exposed. A static, impoverished environment may provide contexts that foster specialisations tailored to that particular environment, whereas a dynamic, rich, diverse environment may foster general coping mechanisms. Thus for example a species that develops an intestine specialised for the absorption of nutrients from a certain plant that is abundant in its environment exhibits context dependence, whereas a species that becomes increasingly more able to consume *any* sort of vegetation exhibits context independence.

Whether an entity exhibits context dependence or independence may simply reflect what one chooses to define as the entity of interest. If an entity splits into multiple 'versions' of itself (as through reproduction), each of which adapts to a different context and thus becomes more context dependent, when all versions are considered different lineages of one *joint* entity, that joint entity is becoming more context independent. Thus for example while different mammalian species are becoming more context dependent, the kingdom as a whole is becoming more context independent.

WAYS OF ACTUALISING POTENTIAL

We now look at how different kinds of evolution fit into the above framework, and how their trajectories differ with respect to the parameters introduced in the previous section.

They are all means of actualising potential that exists due to the state of the entity, the context, and the nature of their interaction, but they differ widely with respect to these parameters.

Evolution of physical objects and particles

We begin by examining three kinds of change undergone by physical entities. The first is collapse of quantum particles under the influence of a measurement. The second is the evolution of quantum particles when they are not measured. The third is the change of state of macroscopic physical objects.

Non-deterministic collapse of a quantum particle

As mentioned above, the change of state of a quantum particle under the influence of a measurement is referred to as collapse. We saw that a measurement has a set of eigenstates associated with it, states that do not change under the influence of the measurement. Thus an eigenstate is deterministic with respect to a measurement. The probability that a genuine superposition state collapses to a particular eigenstate is related to the weight of the vector representing the superposition state in its linear sum over the vectors representing the eigenstates. In general (depending on how many weights are non-zero), many eigenstates are possible states to collapse to under the influence of the measurement. In other words, the collapse is non-deterministic. This means that a genuine superposition state is a state of potentiality with respect to the measurement. This suggests that what we refer to as a context is the same thing as what in the standard quantum case is referred to as a measurement.

Thus a quantum entity exists in a superposition state, and a measurement causes it to collapse non-deterministically to an eigenstate of that measurement. The specifics of the measurement constitute the context that elicits one of the states that were previously potential. Its evolution cannot be examined without performing measurements – that is, introducing contexts – but the contexts unavoidably affect its evolution. Clearly the evolution of a quantum particle is an extreme case of non-deterministic change, as well as of context sensitivity and internalisation, because its state at any point in time reflects the context to which it is exposed. It is not an example of context dependence, since the quantum entity does not require measurements for its survival.

Evolution of quantum particles

The other mode of change in standard quantum mechanics is the dynamical change of state when no measurement is executed, which as mentioned above is referred to as evolution. This is the effect of fields present in the rest of the universe that steer the change of state of the quantum entity, as described by the Schrödinger equation. There is sensitivity to (and possibly internalisation of) context, but it is deterministic. Specifically, if the quantum entity at a certain time t_0 is in state $p(t_0)$, and the only change that takes place is this dynamical change governed by the Schrödinger equation, then state $p(t_i)$ at any time t_i later than t_0 is determined.

For historical reasons, physicists think of a measurement not as a context, but as a process that gives rise to outcomes that are read off a measurement apparatus. In this scheme of thought, the simplest measurements are assumed to be those with two possible outcomes. A measurement with one outcome is rightly not thought of as a measurement, because if the same outcome always occurs, nothing has been compared and/or measured. However, when measurements are construed as contexts, we see that the measurement with two possible outcomes is not the simplest change possible. It is the deterministic evolution process – which can be conceived as a measurement with one outcome, namely always the same – that is the simplest kind of change. This means that in quantum mechanics the effect of context on change is as follows:

- when the context is the rest of the universe, its influence on the state of a quantum entity is deterministic, as described by the Schrödinger equation
- when the context is a measurement, its influence on a genuine superposition state is non-deterministic, described as a process of collapse with non-zero potentiality
- when the context is a measurement, its influence on an eigenstate is deterministic, described as a process of collapse with zero potentiality.

Thus, under the CAP framework, the two basic processes of change in quantum mechanics are united; what has been referred to as evolution is not fundamentally different from collapse. They are both processes of actualisation of potential under the influence of a context. In evolution there is only one possible outcome, thus it is deterministic, whereas in collapse, until the state of the entity becomes an eigenstate there is more than one possible outcome, thus it is non-deterministic.

Evolution of classical physical entities

Classical physical entities are the paradigmatic example of lack of sensitivity to and internalisation of context, and of deterministic change of state. However, theorists are continually expanding their models to include more of the context surrounding an entity in order to better predict its behaviour, which suggests that things are not so tidy in the world of classical physical objects as Newtonian physics suggests. Many macrolevel physical entities exhibit the kind of structure found in quantum mechanics, including entanglement (as indicated by the fact that they violate Bell inequalities, the definitive test for the presence of quantum structure).[47] Moreover, it has been shown that this is due to the existence of situations in which change of state of the entity cannot be predicted owing to lack of knowledge of how it interacts with its context.[48]

Biological evolution

This section is also divided into three parts. The first concerns the earliest life-forms, before the genetic code. The second concerns organisms after coded replication was established but before sexual reproduction. The third concerns sexually reproducing organisms.

The earliest life-forms

Early life-forms were more sensitive to context and prone to internalise context than present-day life because their replication took place not according to instructions (such as a genetic code), but through happenstance interactions. In Kauffman's model of the origin of life,[49] polymers catalyse reactions that generate other polymers, increasing their joint complexity, until together as a whole they form something that can more or less replicate itself.[50] The set is 'autocatalytically closed' because although no polymer catalyses its own replication, each catalyses the replication of another member of the set. So long as each polymer is getting duplicated somewhere in the set, eventually multiple copies of all polymers exist. This basic scenario has been augmented by Deacon,[51] who argues that autocatalytic closure is a necessary but not sufficient condition for replication of such a polymer set to continue over successive generations. He adds that it is also necessary that some polymers spontaneously adhere to one another, forming a spherical vesicle which encloses the polymer set. This 'container' and the autocatalytic set together yield what he calls an 'autocell'. Such a structure is prone to engage in 'budding', where part of the vesicle pinches off and it divides in two. As long as there is at least one copy of each polymer in each of the two 'child' vesicles, it can self-replicate, and continue to do so indefinitely, or at least until it changes so drastically that its self-replicating structure breaks down. (Notice that 'death' of such life-forms is not a particularly noticeable event; the only difference between a dead organism and a live one is that the live one continues to spawn new replicants.) Replication is far from perfect, so 'offspring' are unlikely to be identical to their 'parent'. Different chance encounters of polymers, or differences in their relative concentrations, or the appearance of new polymers, could all result in different polymers catalysing a given reaction, in turn altering the set of reactions to be catalysed. Context was readily internalised by incorporating elements of the environment, and thus there was plenty of room for heritable variation.

Genetic code impedes retention of context in lineage

A significant transition in the history of life was the transition from uncoded, self-organised replication to replication as per instructions given by a genetic code. We saw that before coded replication, a change to one polymer would still be present in offspring after budding occurred, and this could cause other changes that have a significant effect on the lineage further downstream. There was nothing to prohibit inheritance of acquired characteristics. But with the advent of explicit self-assembly instructions, acquired characteristics were no longer passed on to the next generation, so the process became more constrained, robust and shielded from external influence. (Thus for example if one cuts off the tail of a mouse, its offspring will have tails of normal length.) A context-driven change of state of an organism only affects its lineage if it impacts the generation and survival of progeny (such as by affecting the capacity to attract mates, or engage in parental care). Clearly, the transition from uncoded to coded replication, while ensuring fidelity of replication, decreased long term sensitivity to and internalisation of context, and thus the capacity for context independence. Since one generation was almost certainly identical to the next, the evolution became more deterministic. As a result, in comparison with entities of other sorts, biological entities are resistant to internalisation and retention of context-driven change. Though the term 'adaptation' is most closely associated with biology, biological form is resistant to adaptation. This explains why it has been possible to develop a theory of biological evolution that all but ignores the problem of incomplete knowledge of context. As we saw earlier, it is possible to ignore this problem if all contexts are equally likely, or if context has a limited effect on heritability. In biology, since acquired traits are not heritable, the only contextual interactions that exert much of an effect are those that affect the generation of offspring. Thus it is because classical stochastic models work fine when lack of knowledge concerns the state of the entity and not the context that natural selection has for so long been viewed as adequate for the description of biological evolution.

Sexual reproduction

With the advent of sexual reproduction, the contextuality of biological evolution increased. Consider an organism that is heterozygous[52] for trait X with two alleles *A* and *a*. The potential of this *Aa* organism gets actualised differently depending on the context provided by the genotype of the organism's mate. In the context of an *AA* mate, the *Aa* organism's potential is constrained to include only *AA* or *Aa* offspring. In the context of an *aa* mate, it has the potential for *Aa* or *aa* offspring, and once again some of this potential might get actualised. And so forth. But while the mate *constrains* the organism's potential, the mate is necessary to *actualise* some of this potential in the form of offspring. In other words, the genome of the mate simultaneously makes *some* aspects of the *Aa* organism's potentiality possible, and *others* impossible. An organism exists in a state of potentiality with respect to the different offspring (variants of itself) it could produce with a particular mate. In other words, a mate constitutes a context for which an organism is in a state of potentiality. One can get away with ignoring this to the extent that one can assume mating is random. Note that since a species is delineated according to the capacity of individuals to mate with one another, speciation can be viewed as the situation wherein one variant no longer has the potential to create a context for the other for which its state is a potentiality state with respect to offspring. A species can be said to be adapted to the extent that its previous states could have collapsed to different outcomes in different contexts, and thus to the extent its form reflects the particular contexts to which it was in fact exposed. Note also that although over time species become increasingly context dependent, collectively they are becoming more context *in*dependent. (For virtually any ecological niche there exists *some* branch of life that can cope with it.)

Some argue for expansion of the concept of selection to other hierarchical levels, e.g. group selection.[53] We agree with Kitcher[54] that 'despite the vast amount of ink lavished upon the idea of "higher-order" processes', once we have the causal story, it's a matter of convention whether we say that selection is operating at the level of the species, the organism, the genotype, or the gene. It is not the concept of selection that needs expansion, but the embedding of selection in a framework for how change can occur. The actual is but the realised fragment of the potential, and selection works *only* on this fragment, what is already actual. We can now return to the question of what natural selection has to say about the fitness of the offspring you might have with one mate as opposed to another. The answer is of course nothing, but why? Because the situation involves actualisation of potential and non-determinism with respect to context, and, as we have seen, a non-classical formalism is necessary to describe the change of state involved. The CAP perspective also clarifies why fitness has been so hard to nail down. We agree with Krimbas[55] that fitness is a property of neither organism nor environment, but emerges at the interface between them, and changes from case to case. However we do not go along with his conclusion that it is merely a conceptual device, devoid of any substantial physical counterpart. The view of fitness that emerges here is not far in spirit from the 'two-faced'[56] or propensity[57] view, except that potential fitness incorporates all possible evolutionary trajectories under all possible contexts, and actual fitness refers only to the realised segment of this potentiality.

Change of cognitive state in a stream of thought

Recall that the attempt to apply selection theory to thought does not work because selection theory requires multiple, distinct, simultaneously actualised states, whereas cognitive states are not simultaneously selected amongst. Thus an idea certainly changes as it gets mulled over in a stream of thought, and indeed it appears to evolve, but the process is not Darwinian.[58] Having familiarised ourselves with the concept of potentiality, we can now see that the error here is to treat a set of potential, contextually elicited cognitive states of a single entity (a mind) as if they were *actual* states of a *collection* of entities, or possible states with no effect of context, even though the mathematical structure of the two situations is completely different. In a stream of thought, neither are all contexts equally likely, nor does context have a limited effect on future iterations, and the mind changes through interaction with the context to a state that is genuinely new, not just an element of a pre-existing set. So the assumptions that make classical stochastic models useful approximations do not hold. Once again, we have non-determinism with respect to context which introduces a non-Kolmogorovian probability distribution, and a non-classical formalism is necessary to describe the change of state. Sensitivity to context is high (because survival depends on registering and responding to contexts that are dangerous or beneficial), and context-driven change is retained in the form of memory.

Cultural evolution

In this section we look at how cultural evolution fits into the CAP framework.[59]

Culture evolves without a self-assembly code

The basic unit of culture has been assumed to be the behaviour or artefact, or the mental representations or ideas that give rise to concrete cultural forms. Looking at cultural evolution from the CAP framework we ask: what is *really* changing through cultural processes? Because of the distributed nature of human memory, it is never just one discrete 'meme' affected by a cultural experience; it is one's view of how the world hangs together, one's model of reality, or worldview. A worldview is not merely a collection of discrete ideas or memes (nor do ideas or memes form an interlocking set like puzzle pieces) because each context impacts it differently; concepts and ideas are always coloured by the situation in which they are evoked.[60] Indeed it has been argued that a worldview is a replicator.[61] We saw that living organisms before the genetic code – a pre-RNA set of autocatalytic polymers – were primitive replicators because they generated self-similar structure, but in a self-organised, emergent, piecemeal manner; eventually, for each polymer, there existed another that catalysed its formation. Since there were no self-assembly instructions to copy from, there was no explicit copying going on. The presence of a given catalytic polymer, say X, simply speeded up the rate at which certain reactions took place, while another polymer, say Y, influenced the reaction that generated X. Just as polymers catalyse reactions that generate other polymers, retrieval of an item from memory can trigger another, which triggers yet another and so forth, thereby cross-linking memories, ideas and so on into a conceptual web. Elements of a worldview are regenerated through social learning.

Since as with the abovementioned origin of life scenario the process occurs in a self-organised, piecemeal manner, through bottom–up interactions rather than a top–down code, worldviews like the earliest life-forms replicate with low fidelity, and their evolution is highly non-deterministic.

Inheritance of acquired traits in culture

As with the earliest pre-DNA forms of life, characteristics of a worldview acquired over a lifetime are heritable. We hear a joke and, in sharing it with others, give it our own slant. We create a disco version of Beethoven's Fifth Symphony and a rap version of that. The evolutionary trajectory of a worldview makes itself known indirectly via the behaviour and artefacts it manifests under the influence of the contexts it encounters. (For example, when you explain how to change a tire, certain facets of your worldview are revealed, while your playing of a piano concerto reveals other facets.)

Because acquired traits are heritable in culture, the probability of splitting into multiple variants is high. These variants can range from virtually identical to virtually impossible to trace back to the same 'parent' idea. They affect, and are affected by, the minds that encounter them. For example, books can affect all the individuals who read them, and these individuals subsequently provide new contexts for the possible further evolution of the ideas they described and stories they told.

CONCLUSIONS

While replication with variation and selection of particular traits has served as an adequate description of evolution for some time, it does not provide a complete theory of how entities evolve. The reason selection is a significant part of the story in biology is a result of the unusual means of perpetuating form using a self-assembly code, different versions of which get selected amongst for replication, and the death of individuals and the contextually elicited change accrued over a lifetime. But even in biology, selection is not the whole story. It can explain why certain forms propagate while others die out, but it cannot explain how biological form arises in the first place. Moreover, organisms are not the only entities that evolve. Physical, cognitive and cultural entities undergo a similar process of incremental adaptation to the constraints imposed by an environment. There is no reason evolution need involve selection, except as a special case.

This paper has introduced a general framework for characterising how entities evolve through context-driven actualisation of potential (CAP). By this we mean:

- an entity has the *potential* to change in different ways under different contexts
- some aspects of this potentiality are actualised when the entity undergoes a change of state through interaction with the particular context it encounters
- the interaction between entity and context may also change the context, and the constraints and affordances[62] it offers the entity
- thus the entity undergoes another change of state, and so on, recursively.

When evolution is construed as the incremental change that results from recursive, context-driven actualisation of potential, the domains into which we have carved up reality can be united under one umbrella. Quantum, classical, biological, cognitive and cultural evolution appear as different ways in which potential is present due to the state of an entity, its context and the nature of their interaction. They differ according to the degree of: sensitivity to context, internalisation of context, dependence upon a particular context, non-determinism due to lack of knowledge concerning the state of the entity, and non-determinism due to lack of knowledge concerning the state of the context.

The reason potentiality and contextuality are so important stems from the fact that we inevitably have incomplete knowledge of the universe in which an entity is operating. When the state of the entity of interest and/or context are in constant flux, or undergoing change at a resolution below that which we can detect but nevertheless affect what emerges at the entity/context interface, this gives rise in a natural way to non-deterministic change. Non-determinism that arises through lack of knowledge concerning the state of the entity can be described by classical stochastic models (referred to as Markov processes) because the probability structure is Kolmogorovian. However, non-determinism that arises through lack of knowledge concerning the interaction between entity and context introduces a non-Kolmogorovian probability model[63] on the state space, necessitating a non-classical formalism. Historically, the first non-classical formalism was the quantum formalism. This formalism has since been generalised to describe situations involving non-linearity and varying degrees of contextuality. Without going over in detail how different processes of change appear in the CAP framework, let us briefly review some of the more surprising or illuminating outcomes, starting at the microlevel and working our way up.

It has been thought that the two modes of change in quantum mechanics – dynamical evolution of the quantum entity as per the Schrödinger equation, and the collapse that takes place when the quantum entity is measured – are fundamentally different. However, when the measurement is seen to be a context, we notice that it is always a context that could actualise the potential of the entity in different ways. Indeed, if one knows the outcome with certainty one does not perform a measurement; it is only when there is more than one possible value that a measurement is performed. Thus the two modes of change in quantum mechanics are united; the dynamical evolution of a quantum entity as per the Schrödinger equation reduces to a collapse for which there was only one way *to* collapse (i.e. only one possible outcome), hence deterministic collapse. This also holds for the deterministic evolution of classical entities. This is an important result, for evolution and collapse have been held to be two fundamentally different processes.

Looking at biological evolution from the CAP perspective, self-replication appears as a means of testing the integrity of an entity – or rather different versions of an entity – against different contexts. While individuals and even species become increasingly context-dependent, the joint entity of living organisms becomes increasingly context-*in*dependent.The genetic code afforded primitive life protection against contextually induced disintegration of self-replication capacity, at the cost of decreased diversity. The onset of sexual reproduction increased potentiality, and thus possible trajectories for biological form. The CAP framework supports the notion that fitness is a property of neither organism nor environment, but emerges at the interface between them. The concept of potential fitness includes all possible evolutionary trajectories under all possible contexts. Since it involves non-determinism with respect to context, unless context has a limited effect or all possible contexts are equally likely, a non-classical formalism is necessary to describe the novel form that results when an organism interacts with its environment in a way that makes some of its potential become actual (where actual fitness refers only to the *realised* segment of its potentiality). It now becomes clear why natural selection has been able to tell us much about changes in frequencies of existing forms, but little about how new forms emerge in the first place.

The same argument holds for what happens in a stream of creative thought. The mathematical formulation of the theory of natural selection requires that in any given iteration there be multiple distinct, actualised states. In cognition however, each successive mental state changes the context in which the next is evaluated; they are not simultaneously selected amongst. Creative thought is a matter of honing in on an idea by redescribing successive iterations from different real or imagined perspectives, and actualising potential through exposure to different contexts. Thus selection theory is not applicable to the formal description of a stream of thought, and to the extent that creative thought powers cultural change, it is of limited applicability there as well. Once again, a non-classical formalism is necessary.

The notion of culture as a Darwinian process probably derives from the fact that the means through which a creative mind manifests itself in the world – language, art, and so forth – exist as discrete entities such as stories and paintings. This can lead to the assumption that discrete creative artefacts in the world spring forth from corresponding discrete, preformed entities in the brain. This in turn leads to the assumption that novelty gets generated through that most celebrated of all change-generating mechanisms, Darwinian selection, and that ideas and artefacts must therefore be replicators. However, an idea or artefact is not a replicator because it does not consist of coded self-assembly instructions, and thus does not make copies of itself. Moreover, ideas and artefacts do not arise out of separate, distinct compartments in the brain, but emerge from a dynamically and contextually modifiable, weblike memory structure, a melting pot in which different components continually merge and blend, get experienced in new ways as they arise in new contexts and combinations. The CAP framework suggests instead that the basic unit and the replicator of culture is an integrated network of knowledge, attitudes, ideas and so forth – that is an internal model of the world, or worldview – and that ideas and artefacts are how a worldview reveals itself under a particular context.

The CAP framework also provides a perspective from which we can see why the neo-Darwinian view of evolution has been satisfactory for so long, and why it wasn't until after other processes became prominently viewed in evolutionary terms that the time was ripe for potentiality and contextuality to be taken seriously. We also see how unique the DNA code of biological evolution is, as well as the consequent lack of retention of context-driven change. Indeed the effects of contextual interaction in biology are in the long run largely invisible; context affects biological lineages only by influencing the number and nature of offspring. Natural selection is such an exceptional means of change, it is no wonder it does not transfer readily to other domains. Note that it is often said that because acquired traits are inherited in culture, culture should not be viewed in evolutionary terms. It is ironic that this critique also applies to the earliest stage of biological evolution itself. What was true of early life is also true of the replication of worldviews: acquired characteristics can be inherited. Modern life is unique in this sense. Perhaps it is only because Darwinian evolution is such an *unusual* form of evolution that it got so much attention it cornered the term. We stumbled upon the least contextual form of evolution, called it evolution, and then proceeded with a 'theory of evolution' that all but excluded context.

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NOTES

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35. A complex Hilbert space is a vector space over the field of complex numbers.
36. A measurement is described by a self-adjoint operator, which is a linear function on the Hilbert space.
37. For mathematical completeness, we mention that this is only the case when the operator has a point spectrum. Measurements described by operators without a point spectrum must be treated in a more sophisticated way. However, this is of no relevance to the points made here.
38. Each state that is not an eigenstate is a superposition state.
39. There are, however, quantum theories that do not involve collapse.
40. Kolmogorov's axioms, and hence Kolmogorovian probability theories, are named after Andrei Nikolaevich Kolmogorov, who first formulated the axiomatic system for classical probability theory (see A. N. Kolmogorov: *Grundbegriffe der Wahrscheinlichkeitrechnung*; 1933, Berlin, Springer). The theory had in fact existed since the time of Laplace (*Théorie Analytique des Probabilités*, 1812) and had been worked out by various mathematicians, but in a rather informal way. It is well known that the probability calculus of quantum mechanics is non-classical, in the sense that it does not satisfy Kolmogorov's axioms (A. Wilce: 'Quantum logic and probability theory', in *Stanford Encyclopedia of Philosophy*, (ed. E. N. Zalta), Spring 2003 edn, plato.stanford.edu/archives/spr2003/entries/qt-quantlog).
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44. In the SCOP formalism, an entity is described using a state space the algebraic structure of which is given by the set of atoms of a complete lattice (this plays the role of the rays of a complex Hilbert space in quantum mechanics). Measurements are described by Boolean morphisms on the lattice (which play the role of the self-adjoint operators in quantum mechanics).
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58. For in-depth discussion with examples see L. Gabora and D. Aerts: 'Creative thought' (Note 2).
59. This is outlined in more elaborate detail in L. Gabora and D. Aerts: 'Distilling the essence of an evolutionary process, and implications for a formal description of culture', in *Proceedings of Center for Human Evolution Workshop No. 5: Cultural Evolution*, (ed. W. Kistler); 2005, Seattle, WA, Foundation for the Future.
60. L. W. Barsalou: 'Context-independent and context-dependent information in concepts', *Memory & Cognition*, 1982, **10**, 82–93; L. Gabora and D. Aerts: 'Contextualizing concepts using a mathematical generalization of the quantum formalism', *Journal of Experimental and Theoretical Artificial Intelligence*, 2002, **14**, 327–358 (www.vub.ac.be/CLEA/liane/papers/jetai.pdf); D. Aerts and L. Gabora: 'A theory of concepts and their combinations I: The structure of the sets of contexts and properties', *Kybernetes*, 2005, **34**, 151–175, uk.arxiv.org/abs/quant-ph/0402207; D. Aerts and L. Gabora: 'A theory of concepts and their combinations II: A Hilbert space representation', *Kybernetes*, 2005, **34**, 176–205, uk.arxiv.org/abs/quant-ph/0402205.
61. L. Gabora: 'Ideas are not replicators but minds are' (see Note 29).
62. An affordance is a possibility offered by the environment. Thus the presence of food affords the possibility of eating.
63. For example Bayes's formula for conditional probability is not satisfied.

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